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PROSPECTS AND PROBLEMS OF NUCLEAR POWER IN DEVELOPING AREAS

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No. 728 PROSPECTS AND PROBLEMS OF NUCLEAR POWER IN DEVELOPING AREAS

A

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INTRODUCTION

1. The results of developments in the field of nuclear power will become strikingly apparent in the year of this conference as a rapidly increasing number of different power reactor systems become operational. Thus, by June 1962 there were 19 power stations representing 5 reactor types in operation in 6 countries of the world. Their total capacity was 1.6 million kW. It is expected that by the end of 1963 these numbers will increase to 55 stations in 10 countries with a total capacity of 4.5 million kW.

2. A further increase in nuclear power capacity is at present in preparation in all areas of the world, developed and less developed. The planning of nuclear power stations is already at an advanced stage in some of the developing countries, including Brazil, India, Pakistan and the Philippines. For 1966 it is expected that the total capacity of nuclear power in the world will be 9.5 million kW, increasing to 15 - 18 million kW in 1970.

3. The main reason for the interest in nuclear energy is that it has been technically proven as a new source of electric power. The consumption of electric power has in most under developed countries increased very sharply and more rapidly than the total consumption of energy. The possible market for nuclear power in these areas is therefore growing significantly.

4. Furthermore, coal, oil and natural gas are increasingly becoming essential raw materials for important and greatly expanding industries, particularly the petro-chemical and metallurgical industry. Several countries therefore would like to preserve some of their resources of coal, oil or natural gas for these purposes and substitute nuclear energy in the production of electricity.

5. Lastly, the economic life in several countries depends on import of coal or oil. For such countries the addition of uranium to the conventional sources of power production widens the choice of sources of supply for production of electrical energy and therefore lessens the dependence of any one of these sources. From this point of view nuclear power is attractive in regions with a relative scarcity of fossil fuels. Several of the less developed areas are in such regions. For instance the present per capita resources of fossil fuel in South East Asia (excluding China) are 1/10 of those of Western Europe and 1/60 of those of North America.

6. However, nuclear power reactors will only be developed if they offer promises of economic advantages compared with conventional plants. In the latter field there have been substantial technological advances in recent years. The cost per kWh at which nuclear power would be equal to conventional power is therefore at present moving downward. At the same time the development of nuclear power technology is progressing rapidly and it seems that nuclear power plants built now would be able to compete with conventional plants not located closely to coal or oil fields.

7. The less developed countries are naturally interested in determining the most advantageous starting time for their power reactor programme. The data required for such a decision can obviously not be summarized in this paper. It intends to give some guidance in analysis and interpretation of such data by considering successively the technical status of different power reactors, their cost aspects, the steps leading to the introduction of nuclear power, and the materials required for nuclear power production.

ASPECTS OF NUCLEAR POWER DEVELOPMENT

TECHNICAL ASPECTS

8. The technical feasibility of producing electric power from a nuclear plant has been demonstrated. The main problem now is to improve existing reactors or develop new ones which can compete economically with conventional plants under varying conditions. In spite of the fact that nuclear technology is relatively new, having come into existence twenty years ago, and the number of reactor types theoretically possible and deserving investigation is very large, the research and development work carried out so far has already resulted in producing several well-tested and reliable reactor systems. In analysing the current technological status of nuclear power plants, it may be useful to divide them into three broad categories:

(a) Power reactors already in commercial use;

(b) Power reactors promising for the near future; and

(c) Power reactors of advanced concepts whose suitability for industrial use still needs extensive technological and experimental development.

Power reactors already in commercial use

9. This group includes water-cooled reactors (boiling and non-boiling) with enriched uranium as fuel and gas-cooled reactors fuelled with natural uranium. A number of industrial nuclear power stations using reactors of these types are operating in countries with advanced nuclear energy industries and others are being built or planned in other countries, including several developing countries. Their technology incorporates the wide experience accumulated in the use of water and gases as coolants in conventional power engineering practice. Their technical equipment is produced on an industrial scale and they are less complex to service and maintain than reactors of other types.

10. Although these reactors already are in commercial use, they are constantly being improved and simplified as a result of additional experience and development in nuclear technology. They can, however, already now be purchased at a fixed price "turn-key" contract with suitable guarantees for performance.

Pressurized water reactors

11. Pressurized water reactors have been developed extensively in the USA and USSR. In the USA this system is at present regarded as the most advanced in terms of know-how and technology. This is a result of the experience which has been gained in design and operation of naval propulsion reactors, package power plants, the Shippingport, the Yankee and other large nuclear power plants. At present 400 000 kW of pressurized water reactors are in operation, and 500 000 kW under construction in USA, USSR, Italy, and Belgium.

12. The operating experience with the Shippingport and Yankee nuclear power plants has been very encouraging. The power rating of the Shippingport plant has been increased from the original 68 MW to 150 MW, and it has delivered over one billion kW hrs. The performance of the Yankee nuclear power plant exceeded earlier expectations and it is estimated that it is capable of yielding 170 MW instead of the designed 110 MW. This plant was built at a cost of about 25% lower than estimated and within the time schedule. Future improvements in this type envisage simplification in system design, various

components, and in containment. A highly improved fuel performance is foreseen.

Boiling water reactors

13. The boiling water reactor type allows boiling of the water in the core and can supply steam directly to a turbine without the use of a steam generator. This reactor type was developed later than the pressurized water reactor but has, however, developed very rapidly. In part, this is due to the fact that it has been able to take advantage of much of the extensive experience and technology developed in the pressurized water system. At present 350 000 kW of boiling water reactors are in operation and 650 000 kW are being built in USA, USSR, Italy, Japan, and West Germany.

14. The experience with these plants has been very satisfactory. The largest nuclear reactor, the Dresden nuclear power station in the USA, is of the boiling water type and has put out about 2 billion kW hrs at a high availability factor. Experience indicates that with some modification, the rating of the plant can be increased from 180 to 270 MWe. Many design variations and improvements indicating high potentialities of boiling water reactors are being explored. These improvements include internal steam separation, higher power density, simplified containment and higher utilization of fuel.

Nuclear superheat

15. The current designs of the boiling water and the pressurized water reactors produce saturated steam at relatively low temperatures (for instance, in the case of the Dresden plant, the steam produced is at 540°F and 1000 psi.) This involves the use of specially built large turbines which are relatively costly. It is expected that the production of superheated steam in reactors will have some economic advantage in comparison with reactors producing saturated steam. Nuclear superheat may be incorporated in pressurized water reactors, boiling water reactors, as well as several other types of reactors.

16. Experiments at the First Atomic Power Plant in the USSR demonstrated the technical feasibility of nuclear superheat in this type of reactor. A large nuclear power plant with reactors based on nuclear superheat is at present under construction in the Ural region of the USSR. In the United States several projects are directed at demonstrating the technology of reactors with nuclear superheat. Two nuclear superheat demonstration power plants, namely the BONUS (16 MWe) and Pathfinder (60 MWe) are under construction and will be critical by early 1963. Their operation is expected to yield valuable information on the technical feasibility and economics of nuclear superheat.

Gas-cooled reactors

17. These reactors have been developed primarily in the United Kingdom and France. The first gas-cooled power reactor, Calder Hall (UK), went into operation in 1956 and since then the installed capacity of such reactors has risen to 754 000 kW and will go up to 4 million kW by 1966, making it the leading reactor type in terms of kW installed.

18. The experience with these gas-cooled and graphite moderated reactors fuelled by natural uranium has established them as one of the reliable producers of nuclear power. Calder Hall's availability factor was 85% over a period of five years, in spite of the fact that it does not refuel during operation. Its heat output has increased by 25%. The average fuel utilization is also expected to increase.

19. These reactors have a good record of performance. To compete successfully with other types which are developing rapidly, they are, however, being improved so as to achieve higher power density with consequent reduction in size and increase in coolant temperature, and higher fuel utilization. This implies the use of enriched uranium and possible use of other coolants such as helium.

20. The Advanced Gas-Cooled Reactor (AGR) in the United Kingdom, which went critical in August 1962, using enriched uranium fuel and carbon dioxide as coolant, and the Helium-cooled HTGR in USA, to be critical in 1963, represent significant improvements over earlier gas-cooled reactors. Larger plants of this type may use pre-stressed concrete pressure vessels instead of steel ones to reduce costs.

21. There are also the semi-homogeneous gas-cooled reactors with enriched uranium oxide and uranium carbide as fuel. The fuel is dispersed in graphite which serves as the moderator as well as cladding material. Examples of this reactor type are the 40 MWe helium-cooled HTGR in USA and the 15 MWe helium-cooled pebble bed AVR in West Germany. If the uranium fuel is mixed with thorium, the utilization of fuel in these reactors may eventually be as high as 80 000 MWd/t resulting in a substantial reduction in fuel cycle costs.

Power reactors promising for the near future

22. This category includes concepts which have advanced well beyond the experimental stage and are being demonstrated in the form of prototype full-scale power plants. They have a sound basis in technology but their feasibility and technical and economic performance as central station plants has yet to be demonstrated. Commercial applications of these reactors can be envisaged in the latter half of the 1960's, if the operating experience with the prototypes proves satisfactory. These include three important types:

(a) Heavy water reactors,

(b) Organic moderated reactors,

(c) Sodium graphite reactors.

Heavy Water Reactors

23. The first heavy water prototype power reactor, NPD, with 20 MWe output, went into operation in Canada in April 1962. It was preceded by an experimental boiling heavy-water reactor at Halden in Norway in 1959. NPD has benefited greatly from the extensive technical experience existing with heavy water research reactors as well as the know-how developed with light-water reactors. The advantage of this type is the fact that the use of heavy water as moderator and coolant permits the use of natural uranium as fuel and a high fuel utilization. This makes it possible to discard the burned fuel elements without significant economic penalty, thus avoiding the need for reprocessing. Those countries which have indigenous resources of natural uranium and would like to base their nuclear power programmes on these resources, could find this feature attractive. The need for importing or producing large quantities of heavy water, however, would remain.

24. The initial operation of NPD has been very encouraging and it will provide valuable information for a large 200 MWe CANDU power reactor, scheduled for completion in Canada by 1964. A heavy water moderated and cooled reactor, R-3, in Sweden will produce 9 MW of electricity and 55 MW of steam for space heating. The 17 MWe Carolina-Virginia reactor, which due to its small size is fuelled with slightly enriched uranium, is expected to be critical late in 1962.

25. A number of variations of heavy water moderated reactors are possible through the use of other coolants such as organic substances, gas, and light water. Direct or indirect cycle, production of nuclear superheat, refuelling during operation, etc. are also possible.

26. Among the variations being tried out are organic cooled heavy water systems in Canada, Italy and Spain, a 150 MWe gas cooled natural uranium heavy water reactor in Czechoslovakia, and an 80 MWe EL-4 reactor of the same type in France.

27. Another promising variation in the heavy water concept is the spectral shift reactor which employs a varying mixture of heavy water and light water and can achieve very high fuel utilisation. No prototype of this concept is under construction at the moment.

Organic moderated reactors

28. These reactors employ an organic substance both as a moderator and coolant which gives it certain advantages compared with water cooled reactor. The organic does not react with uranium or carbon steel, which permits the use of more conventional materials. The low pressure in an organic reactor adds to its safety and it can deliver superheated steam.

29. The limitations of this system include the fact that the organic substance decomposes under irradiation, requiring new substance to be added to the extent of 0.5 to 1 lb per MWh of heat. This adds to the operating costs. The heat transfer characteristics of organic materials together with the possibility of fuel element fouling are also to be considered. Since the organic is a solid at room temperature, all the organic circuits have to be kept at 500°F, necessitating the use of steam tracing, which requires additional maintenance.

30. Based upon experience gained with the Organic Moderated Reactor Experiment, organic moderated Piqua reactor of 11.4 MWe was completed in USA and is expected to be critical by end 1962. The performance of this reactor will be of great value in establishing the suitability of this concept for central station application. If the plant is successful, a large 300 MWe plant may be built in the later 1960's. The potential improvements in the organic systems include use of organics less susceptible to radiation decomposition, higher operating temperatures, and power densities.

Sodium Graphite Reactors

31. Among the systems capable of yielding high temperature and high pressure steam to suit the standard turbines, the sodium graphite reactors seem to be a practical possibility. The first power plant of this type (the Hallam Nuclear Power Facility in the USA with an output of 75 MWe) went into operation in October 1962. It is likely that a large 300 MWe plant of this type may be built towards the end of the 1960's in the United States.

32. This system utilises the excellent heat transfer properties of sodium which, at relatively low flow rates, can extract large amounts of heat from the reactor and generate superheated steam through a heat exchanger. The low pressure of the system obviates the need for a containment shell. The drawback is that sodium reacts with water and air and also becomes radioactive. This calls for special precautions.

Power reactors of advanced designs

33. This category includes the advanced types of reactors which are still in the early stages of development and require extensive technological data and experience before their suitability for large-scale industrial applications can be established. Most of these reactors are not expected to be ready for construction for commercial use before the end of the 1960's or in the early 1970's. They include aqueous homogeneous reactors, breeder reactors of both fast and thermal type, molten salt reactors, etc.

34. In all these instances, some fundamental problems remain to be solved, including those relating to reactor physics, materials, components, fuel, control and safety. Much money and effort will have to be spent on experimental and technological testing of the reactors in this group before their technical and economic superiority over the reactors in the first two groups can be proved.

Long-term prospects of using thorium and plutonium

35. In the long run, the impact which nuclear power may have on the world energy supply will depend largely upon the ability of nuclear reactors to utilize available nuclear fuel to the maximum extent. The present day reactors which are in commercial operation burn only a fraction of the uranium fed into them. With this low utilization of nuclear fuel, the energy available from the low cost uranium ores would represent only a small portion of what is known to be available from fossil fuel reserves. However, the research and development work conducted so far has established that it is possible to achieve a very high utilization of nuclear fuel by re-using or re-cycling the unused portion of fuel left in the reactor core, and by breeding additional fissionable material from fertile material. Thus the amount of energy available from nuclear fuels will be many times that available from fossil fuels.

36. In terms of fuel utilization, the nuclear power reactors fall into three main categories, i.e. burners, convertors and breeders. A burner reactor uses only fully-enriched uranium or plutonium and burns it without producing any fissionable material during the process. A convertor reactor uses a mixture of enriched uranium or plutonium with natural uranium or thorium and while it burns this enriched material it produces considerable quantities of plutonium or the isotope of uranium U^{233} in the core, some of which contributes significantly to the heat output from the reactor. A breeder reactor is a convertor, which produces more fissionable material than it starts out with, so that at the end of the cycle there is a net gain of fissionable material. There are two types of breeder reactor; one where the neutron energies are very high, called the fast breeders, and the other where neutrons are slow, called the thermal breeders.

37. The possibility of using thorium and natural uranium as a basis for a nuclear power programme is of special interest to countries which have considerable deposits of thorium and uranium ores. A number of less developed countries, including India, Brazil and the UAR, belong to this group. It may, therefore, be useful to review briefly the technical status and future potential of thorium and plutonium based convertor and breeder reactors.

38. Thorium is an important fertile material but, unlike natural uranium which contains 0.7% of U^{235}, it contains no fissionable material and cannot be used as the sole fuel for a reactor. However, thorium together with fissionable material (either U^{235}, plutonium, or U^{233}) can be used to fuel converter or breeder reactors. If the reactor is a breeder, it will be possible,

after having accumulated an inventory of U^{233}, to operate on a thorium/U^{233} breeder cycle, with no further need of U^{235} or plutonium. The reactor fuel cycle would be sustained by fresh supplies of thorium only.

39. At the present time thorium is used as a fertile material in a few power reactors and reactor experiments. The 255 MWe Consolidated Edison Thorium Reactor (CETR), which went critical in August 1962, uses a mixture of highly-enriched U^{235} and thorium oxides. The U^{233} produced in the core is expected to contribute 10 - 20% of the heat generated. The 20 MWe Elk River Reactor, which went critical in October 1962, also employs a mixture of thorium oxide and highly-enriched uranium. Italy has considerable interest in thorium cycle and under arrangements with the United States the Elk River fuel may be re-processed and refabricated in Italy.

40. The gas-cooled semi-homogeneous reactors DRAGON in the UK and the HTGR in the USA, both scheduled for operation by 1964, are based upon fully-enriched U^{235} and thorium carbides dispersed in graphite and a considerable portion of the heat produced in these reactors is expected to come from U^{233} produced in the core. Thorium might also be used in aqueous homogeneous heavy water moderated reactors or spectral shift reactors which could be breeders. India, which has large deposits of thorium, is conducting considerable research directed toward thorium cycle.

41. All the above-mentioned reactors are basically experimental and are expected to yield valuable information. Nevertheless, the unknowns of the present time are so numerous that the number of U^{233}/thorium breeders constructed in this decade will be comparatively small. U^{233} as produced in power reactors contains small quantities of U^{232} and its daughter products, which are strong gamma emitters and must be handled remotely. Such problems will be resolved in due course and it is likely that thorium reactors will play an important part in nuclear power production in the future.

Plutonium-fuelled reactors

42. Plutonium may be produced in natural uranium thermal reactors. Thus, a country having large uranium reserves could conceivably start its nuclear power programme with the natural uranium system and produce enough plutonium over a period of time to go on to plutonium/uranium breeders. Plutonium can also be used in place of U^{235} in ordinary converter reactors.

43. Recently, the long-term desirability of using plutonium as power reactor fuel has become increasingly evident. Consequently several countries are now pursuing research and development programmes to study techniques for fabricating plutonium-bearing fuel elements, to develop remote methods for recovery of spent fuel and refabricating plutonium fuel elements, etc. The value of plutonium as reactor fuel will be determined by the cost of these fuelling operations and by fuel performance and fuel lifetime in comparison with an alternative enriched uranium fuel cycle. It is interesting to note that many developments in plutonium fuel technology, such as remote fabrication of fuel elements, might be immediately applicable to thorium/uranium-233 technology, and that techniques for producing fuel elements for thermal reactors or converters might be adapted to fabrication of fuel for fast breeder reactors.

44. Several reactor experiments and prototype power plants using plutonium have been built and are under construction. The plutonium oxide fuelled BR-5 in the USSR has operated since 1959 and plans are under way for larger (250 and 1000 MWe) fast plutonium fuelled reactors. In the USA the 16.5 MWe Experimental Breeder-2 will have a second core of plutonium and it is a fully integrated

nuclear power station with facilities for fuel fabrication by remote control and reprocessing. The LAMPRE, using molten plutonium, has been in operation since 1961. The water moderated plutonium Recycle Test Facility is developing information on recycling of plutonium. In France, the RAPSODIE reactor, using uranium oxide and plutonium oxide, is expected to go critical in 1964.

45. All the foregoing reactors and other experiments are expected to yield the essential data necessary for constructing commercial breeder reactors which may go into operation in the early 1970's. Some countries visualize that a considerable part of the nuclear power plants built after 1975 will consist of plutonium-uranium fast breeders.

COST ASPECTS

Summary of cost data

46. The aforegoing review of the technical progress of nuclear power shows that more and more information necessary for calculations of nuclear power costs is becoming available. However, only limited operational experience has so far been gained. Hence much of the technical and economic data at present available are subject to reassessment as technology continues to develop.

47. Nuclear power has advanced to the point where some reactor types if built with the technology known at present are expected to prove competitive with modern conventional power stations operating in areas where conventional fuel prices approximate 40 cents per million BTU's ($1.60 per million kilocalories). This price range prevails in several areas of the world which are not located closely to coal or oil fields. In the USA it has been announced that a boiling water reactor with a capacity of 325 MWe will be built at Bodega Bay, California, which is expected to be competitive at conventional fuel prices of 35 cents per million BTU's.

48. The main components of nuclear costs are capital costs, fuel cycle cost, and costs of operation and maintenance of the power station. These vary widely from one type of reactor to another. A brief summary of these costs is given below.

49. As regards capital costs, gas cooled, graphite moderated reactors in the 500 MWe size cost about $280 per kW of installed capacity. Water reactors in the 300 MWe size cost about $200 to $250 per kW of installed capacity. In the field of smaller reactors, a comprehensive effort at developing a variety of possible reactor systems is now yielding remarkable results. The variety of reactors which have been investigated is, however, such that their capital costs cover a wide range extending from $380 to $600 per kW of installed capacity, with light water and organic moderated reactors appearing as the leading contenders.

50. Fuel cycle costs are at present in the range of 2 to 4 mills per kWh for light water and gas cooled reactors. For heavy water reactors of the CANDU type, a fuel cycle cost of about 1.2 mills per kWh is predicted. Such fuel cost figures should, however, always be considered in the light of the cost structure of the nuclear fuel cycle which is radically different from that of conventional fuels and furthermore varies from one reactor system to another. Whereas the conventional fuelling cost is essentially the cost of fuel consumed, the cost of uranium consumed is but one of the components of the nuclear fuelling cost, and in most cases smaller than the cost of preparing and fabricating the fuel. Also, in most systems the credit for the plutonium contained in the irradiated fuel elements is an important determinant of total fuel costs

51. Thus, in gas cooled reactors using natural uranium metal fuel with Magnox cladding, the uranium consumption cost is perhaps 0.8 to 1 mill/kWh, while fabrication cost may be 1.3 to 1.7 mills/kWh and plutonium credit might amount to 0.8 to 1 mill/kWh. For light water reactors, the uranium consumption cost might be 1 to 2 mills/kWh, the fabrication cost 1 to 2.5 mills/kWh, and the plutonium credit 0.4 to 0.8 mill/kWh. In the case of heavy water reactors with natural uranium fuel for which the spent fuel is not reprocessed and for which no plutonium credit is taken, the uranium consumption cost may be about 0.4 to 0.5 mill/kWh and the fabrication cost 0.7 to 1 mill/kWh.

52. The cost of operation and maintenance for nuclear stations is not yet well established, but is expected to be in the range 0.7 to 1.2 mills/kWh.

53. On the basis of the above figures and assumptions concerning the annual charge for capital cost and the percentage of the plant's total capacity utilized per year, the generating cost per kWh can be calculated. Under the reasonable assumptions of a 10% annual charge rate and of an 80% load factor, the generating cost would be 6 to 8 mills per kWh for stations in the 300 MW range and 9 to 12 mills for stations in the 50 MW range. These figures are illustrative only and subject to the qualifications outlined in the following.

Evaluation of cost data

54. The average generating cost over the life of a specific nuclear power station is subject to a number of uncertainties covering a much wider range than those affecting the operation of a conventional unit. However, more often than not they are uncertainties about the time and extent of future savings rather than about future additional costs. Indeed, in most cases a cost ceiling may be quoted and even guaranteed by the builder of the nuclear plant on the basis of present conditions while a minimum cost is more difficult to estimate.

55. Thus, it appears unavoidable that nuclear power costs for a given reactor system will take the form of a range between an upper and lower limit. In estimating this range and drawing conclusions therefrom, several problems must be faced which might be best reviewed in the light of the objectives of any cost analysis. These are:

(a) The establishment of an estimate of total investment costs and of future fuel costs, and operation and maintenance costs, which the construction and operation of a power plant will entail;

(b) An allocation of these total expenditures to the units of energy which the power plant is expected to produce over its life or, in other words, an evaluation of generating costs;

(c) A comparison of the generating cost figure so obtained with those of other possible alternatives.

56. At each of the steps enumerated above there are some difficulties in obtaining single figures of unrestricted applicability. These questions are reviewed in the following.

(a) Estimation of total investment, fuel, and operation and maintenance costs

57. The difficulty in this field lies in making an accurate estimate of future fuelling costs. The fundamental difference with a conventional power cost assessment stems from the fact that the fuelling cost of a nuclear plant is not determined by fresh fuel prices alone. No less important is the amount of

energy which can be extracted from the fuel before it must be reprocessed or discarded and the costs incurred for its preparation and fabrication. In both aspects improvements have been so rapid and prospects for the future so favourable that present figures can only be viewed as an upper limit. On the other hand, the present prices paid for the plutonium contained in the irradiated fuel can hardly be expected to prevail for the life of the reactor.

58. There remains a series of formal difficulties which arise from inclusions or omissions of various items in the cost figures quoted by reactor builders. This applies particularly to capital costs which may or may not include such items as interest during construction, commissioning of the plant, site improvement, etc. A careful breakdown of what total cost figures actually cover is therefore indispensable.

59. Another significant problem is the extrapolation of costs quoted by one country to the conditions prevailing in another. Apart from the obvious element of transport costs, there are different adjustments of construction time and total wages and salaries to which no rule of thumb can be expected to apply and which must, therefore, be the subject of thorough investigation in each specific case.

(b) Estimation of generating costs

60. Assuming that all the initial data have been estimated with a reasonable degree of accuracy, the next problem is to derive from them a generating cost figure for the kWh's produced. Here again the estimator is faced with technical, economic and accounting uncertainties.

61. With regard to technical factors, both plant life and load factor which affect generating costs must for the time being be assumed, since no power reactor has been operated for the whole of its expected operational life. The assumptions usually made (20 years life and 80% load factor) are on the conservative side, since it is likely that nuclear stations will operate just as long as conventional stations (for which a 25 - 30 years life is usually assumed) and since utilization factors achieved in some of the recent power reactors had been of the order of 87 - 90%.

62. Just as important is the possibility of achieving a power output substantially exceeding that provided by the original design, thus lowering estimated unit capital costs proportionately. The striking improvement achieved in the power output of the Shippingport, Yankee and Dresden reactors shows the reality of such possibilities and their effect on final generating costs.

63. Among the economic factors, the interest rate used in the calculations plays a decisive role. A high interest rate will, of course, favour plants with relatively low investment (and relatively high fuel) costs, while a low rate will favour an alternate plant with higher investment costs but lower fuel costs.

64. With respect to the accounting questions, the determination of generating costs is complicated by the existence of different methods of computation. The problem of assigning to the kWh produced a unit cost which will accurately reflect the long series of expenditures incurred at different times for the construction, fuelling and operation of a power plant, is not new or specific to nuclear power although it is particularly complicated in this case because of the irregularity of the fuel expenditures and the relatively large decreases which can be anticipated in the near future. A general solution can be considered along the following lines:

(a) Selecting a point of reference in time, say the date of first full power operation;

(b) Discounting all expenditures to that date and adding them;

(c) Discounting all the expected energy production to the same date;

(d) Dividing the first discounted sum by the second.

This yields a single generating cost figure which might be interpreted in the following way. If all the kilowatt hours expected to be produced by the reactor were sold at this figure the stream of revenues obtained from sales would be exactly equivalent to the series of capital, fuel, and operation and maintenance costs required for the construction, fuelling and operation of the reactor.

65. An objection to this method is that it involves forecasts about the future which are at best uncertain. Another is that it requires a large amount of work. Consequently, approximate methods are in use in various countries which are described in a document published by the IAEA.(1) When they are applied to the reactors, fuel procurement and management conditions for which they have been designed, their results are so close to those of the above described method that they can safely be used.

(c) Generating cost comparisons for different power plants

66. The generating costs obtained for two or more power plants of the same output but with different capital, fuel, and operation and maintenance expenditures will permit an economic comparison of their merits only if they are expected to render the same services to the power system in which they will operate. This is an important qualification, especially in the case of an economic comparison between a nuclear and a conventional unit, considering that in most cases the two plants would not be operated similarly over the course of their life.

67. The very low fuel costs of a nuclear power plant will dictate its retention on base load from which it could only be displaced by more efficient successors, while the conventional unit will presumably move from base load to peak load operation at a much faster rate. Consequently, while the two plants will produce the same amount of energy during the first few years, this situation is not likely to prevail throughout their lives. If nuclear power is expected to represent a large share of the total capacity of a power system, nothing short of a computation of total system costs for each of the contemplated alternatives can yield fully dependable results.

STEPS LEADING TO THE INTRODUCTION OF NUCLEAR POWER

68. Assuming that a less developed country is interested in the possible application of nuclear power, the question arises as to what steps should be taken leading towards actual construction of a power station. There is no standard answer or approach to this question because the conditions and needs as well as the state of development differ widely from one country to another. Nevertheless, it may be useful to outline some of the important steps which are common in most cases. These steps are:

(a) A comprehensive survey of indigenous energy resources such as hydropower, coal, oil and gas. This would indicate the supply position regarding conventional energy and its cost range. If energy resources are abundant, cheap and properly distributed in relation to the load demand, then the need for any alternate source of energy such as nuclear power would not be urgent;

(b) An estimate of the demand for electric power in the area and the preparation of a long-term plan to meet this demand. This would indicate the size and timing of additional capacity which must be built;

(c) An estimate of the initial cost, operating expenses and generating costs of conventional plants to meet the projected demand and a preliminary comparison of these with the costs of a nuclear power plant. If this preliminary comparison shows encouraging prospects for a nuclear plant, a detailed economic comparison may be justified;

(d) Further detailed comparisons between conventional and nuclear power should take into account several factors such as financing, interest charges, local and foreign exchange expenditures, extrapolation of costs to the conditions of the country, and the contribution of local industry, services and materials;

(e) If an exhaustive economic comparison is in favour of nuclear power, arrangements for financing must be considered prior to calling for international bids on the basis of detailed specifications;

(f) The evaluation of bids should be undertaken very carefully and with the help of experts and consultants as necessary, so that the final selection of the type of reactor is based on the best available technical and economic information and analysis;

(g) Concurrent with these efforts it may be necessary to attend to other matters such as atomic legislation, and undertake a training programme for the technical staff.

69. In the enumeration of phases given above, no time scale is given. At least four years should be allowed for the construction and commission of a nuclear power station and about two to three years for the initial surveys and studies. This compares with about five years for a conventional thermal station project.

CONCLUSIONS

70. From the preceding survey of the technical status of nuclear power and of the cost data available, the following conclusions may be drawn:

(a) The possibility of producing nuclear electricity on an industrial scale has been demonstrated for several reactor systems operating under conditions of great reliability and high utilization factors. It is about to be confirmed for several other types expected to start operating in the near future,

(b) The generating costs expected to be achieved by some of the large reactors under construction in advanced countries would be competitive with those of conventional stations of the same size operating in relatively high fuel costs areas. These estimates still have to be fully tested since no power reactor has been in operation for more than seven years (in most cases much less);

(c) An intensive effort at developing reactors of smaller size in the 50 MW range is yielding important results. The variety of the systems investigated leads to a rather wide range of costs all of which are considerably higher than for large reactors;

(d) The question of introducing nuclear power reactors for developing countries with limited resources of conventional energy is therefore beginning to change from one of principle to one of suitable timing;

(o) The problem of timing is, however, of fundamental importance and the best possible investment of large capitals depends on its correct solution. This solution must be based on a careful analysis of existing domestic energy resources, of forecasts of future electric power demand and of the costs of alternative plans for meeting this demand. It must at the same time make allowance for the relatively long period required for the bringing into operation of a nuclear power plant, as well as for the importance of this plant for the future nuclear power programme of the country concerned.

MATERIALS REQUIRED FOR NUCLEAR POWER PRODUCTION

71. Materials required for nuclear power production include not only the nuclear fuel material, but many other materials for use as moderators, coolants, controls, cladding and structural purposes. The main and presently the only fuel material of practical importance is uranium, used in its natural form or artificially enriched in the isotope 235. The possibility of using thorium is envisaged and much research on this technique is going on throughout the world.

72. For moderators non-metals, such as natural or heavy water, organic compounds, and graphites, are mainly used but the possibility of using beryllium or beryllia for this purpose is being investigated.

73. Coolants used in atomic energy for heat exchange purposes include water, heavy water, organic compounds, gases such as carbon dioxide, nitrogen and helium, and liquid metals such as sodium. Control materials include cadmium and boron, while cladding materials include magnesium alloys, zirconium alloys, stainless steel, aluminium, beryllium and niobium.

74. Of all these materials, uranium is the one most likely to be required in large quantities. However, depending on the success of research under way, thorium and beryllium might also be required in substantial amounts. The other materials mentioned are not likely to present much difficulty in production from known sources to meet expanding needs adequately.

75. It was originally thought that world supplies of uranium would be insufficient to meet the expanding needs for nuclear energy but sustained geological search has shown this mineral to be much more plentiful than had been expected. Similarly, abundant resources of thorium minerals exist sufficient to meet foreseeable needs arising from the result of research on thorium techniques. However, it is doubtful if the world supply of beryllium minerals would be adequate to sustain a greatly expanded demand based on present prices, although research on mineral concentration of beryllium minerals might change this situation.

76. Thus, attention might be concentrated on uranium, thorium and beryllium as materials which might be in short supply in future nuclear power expansion.

77. The largest known deposits of uranium bearing minerals are found in Canada, South Africa, USA and France, while smaller commercial deposits are found in Australia, Congo, Portugal, Japan, Madagascar, Argentina and Mexico. Total known reserves of uranium recoverable at an economic price are of the order of one million tons in the western countries while known reserves of at present sub-economic uranium are about 5 million tons. The present trend of production is downward and the production in western countries in 1961 was about 35 000 tons, and production is likely to be voluntarily reduced during

the next five years. The main producers were USA, Canada and South Africa, with production of 17 350, 9720 and 5100 tons of U_3O_8 respectively. The remaining production was shared between France, Australia, Madagascar, Gabon and Portugal.(2)

78. Consumption in the next 8 - 10 years might well be below production capacity. Estimation of future requirements of uranium is difficult due to the unknown factor of military requirements which at present accounts for the main consumption. Estimates of requirements for peaceful purposes in western countries show the total tonnage required to be less than 70 000 tons total in the next five years.(3)Thus a surplus of supply over demand is assured even if no falling off of military requirements should take place.

79. Large deposits of thorium bearing sands are found in India, Brazil, Ceylon and Australia while substantial reserves of thorium (about 20% of the western total) occur in the uranium ores of Canada. The total known reserves of thorium in known deposits is of the order of 1 million tons, while it is doubtful if present annual consumption exceeds 1000 tons.

80. Present world production of beryllium is derived by hand picking from pegmatites. Recently some success has been achieved in flotation of finer grained disseminated beryllium ores, but the cost factor may limit large-scale application. Current production and consumption of beryl (containing about 11% BeO) is of the order of 10 000 tons per year, and an arbitrary estimate of known world reserves has been given as 14 000 tons of contained BeO. Obviously estimation of reserves from pegmatites is difficult, and reserves would be substantially increased if disseminated beryllium minerals could be successfully concentrated. In present conditions, and considering other expanding requirements for beryllium, reserves and production might be regarded as inadequate to meet future needs.

ROLE OF THE INTERNATIONAL ATOMIC ENERGY AGENCY

81. One of the Agency's statutory functions is to assist the development and practical application of atomic energy, including the production of electric power, with due consideration for the needs of the underdeveloped areas of the world.

82. The Agency provides services and assistance which are useful for all its Members, but some activities are particularly or exclusively of importance for the less developed areas of the world. Of importance for all countries is the Agency's contribution in such fields as health and safety procedures, radioactive waste disposal, reactor safety and third party liability. Another contribution is the Agency's collection and dissemination of scientific information by means of conferences, symposia and seminars, and by its publication programme. Subjects of conferences etc. have been, for instance, fuel element fabrication, small and medium power reactors, reactor experiments, reactor safety, and hazards of evaluation techniques.

83. The Agency can foster group undertakings as has happened, for instance, with regard to the reactor physics programme conducted at the NORA critical assembly in Norway. It also acts as an intermediary in the supply of nuclear fuel which has been requested by the Congo, Finland, Japan, Norway, Pakistan and Yugoslavia.

84. The Agency's statutory obligations towards the less developed areas have been discharged by conducting, at the request of the countries concerned, economic power surveys such as those carried out in Finland, Pakistan,

the Philippines, El Salvador, and Yugoslavia. Once a preliminary study has given encouraging results, the IAEA can continue its assistance by providing experts to advise on such technical points as the choice of reactor type, the siting of the power plant, safety and hazards evaluation and the preparation of the necessary legislation, as well as to assist in drawing up specifications. It can also organize an international panel to study tenders for construction and arrange for the training of staff. Finally the Agency can assist by helping to obtain the nuclear fuel and by facilitating the making of financial arrangements.

85. In the field of nuclear power costs, the Agency undertakes studies in developed countries so that the best practical solutions can be evolved for the specific needs of the less developed areas. In this connection, the Agency sends periodic missions to the USA and Canada at the invitation of the Governments to follow the design, construction, operation and economics of a certain number of small and medium power reactors. The information obtained is provided to Member States.

86. Studies on nuclear power costs are only of interest if there is a reasonable degree of comparability of the results. With this in view, the Agency has in November 1961 issued a methodological study of nuclear power costing. This study is now being expanded to the economic problems which arise when a nuclear power plant is integrated in an electrical distribution network.

87. Further, the Agency has upon request provided international expert teams to perform reactor hazards evaluations. Such evaluations have been made in the Netherlands, the Philippines, Switzerland and Thailand.

88. Like the other organizations in the UN family, the Agency has a programme of the provision of experts, equipment and fellowships, financed from the Agency's own resources and from the Expanded Programme of Technical Assistance (EPTA). Several advanced countries have offered to the Agency to accept fellows from other Member States to be trained in the operation of nuclear power reactors.

89. The coming decade has been designated by the UN as a development decade. This decade will be very important for nuclear power. By the end of that period, if expectations are correct, nuclear power will cease to be a question of experiment and of testing of prototypes and will become an established part of the world's industry. The Agency is prepared to perform its role in this development.

References

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List of Abbreviations

BONUS	boiling nuclear superheater power station
BTU	British thermal units
EGCR	experimental gas-cooled reactor
mill	one-thousandth of a dollar
MWd	megawatt day
MWd/t	megawatt day/metric ton uranium
MWe	megawatt electric
NPD	nuclear power demonstration
OMRE	organic-moderated reactor experiment
psi	pounds/square inch
SGR	sodium graphite reactor
t	metric ton

NOTE

All sums of money are expressed in United States currency.

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